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5 life and livelihood.

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## **Changing storminess and global capture fisheries**

**Climate change-driven alterations in storminess pose a significant threat to global capture fisheries. Understanding how storms interact with fishery social-ecological systems can inform adaptive action and help reduce the vulnerability of those dependent on fisheries for life and livelihood.**

Fisheries are an important source of food, nutrition, livelihoods and cultural identity on a global scale. Fish provide 3.1 billion people with close to 20% of their animal protein<sup>1</sup>, and are relied upon for vital micro-nutrients, which are particularly critical to the health of children and pregnant women<sup>2</sup>. Capture fisheries and aquaculture are estimated to support the livelihoods of 12% of the global population and 38 million fishers regularly risk their lives in one of the most dangerous jobs on Earth<sup>1</sup>. Despite its dangers, fishing is an important source of cultural identity and well-being for fishing communities around the world<sup>3</sup>.

In addition to ocean warming and acidification, changing storminess is a climate stressor that affects marine life and habitats (Fig. 1a), with potential negative consequences for fish catch and the well-being of coastal communities. Changing storminess also poses a direct risk to fisheries. Storms directly affect fishing effort, posing a physical threat to fishers, their vessels and gear, as well as to fishing communities and their infrastructure. Whilst ocean warming may alter potential fish catch over the next 50 to 100 years<sup>4</sup>, changing storminess has the potential to cause more immediate and catastrophic impacts. The 21<sup>st</sup> century has already witnessed many tropical, extra-tropical and thunder storms that have claimed thousands of fishers' lives, destroyed fishery-dependent livelihoods and assets, and disrupted the production of commercial inland and marine capture fisheries (Fig. 1b).

Storminess reanalysis and projection studies are growing in number and geographic scope (Fig. 2). However, uncertainty in past and future storminess from global and regional climate models remains high as a result of widespread variation in analytical methods, poor historic observational data and the challenge of distinguishing externally forced climate changes

from natural internal climate variability<sup>5</sup>. Attribution of particular extreme weather events to anthropogenic climate forcing is problematic, and especially so for storms<sup>6</sup>. Thus, extreme weather event attribution is an expanding area of research and examples for storm events are beginning to emerge<sup>7</sup>.

Despite the challenges of modelling the location, frequency and intensity of storms, there is sufficient certainty for the IPCC to conclude for the North Atlantic basin, where fisheries productivity is high and historic storm data is particularly rich, that the frequency of the most intense tropical storms has increased since the 1970s<sup>5</sup>. A recent review of future winter storminess studies in Europe, ranging over periods spanning 2020–2190, predicts increases in storm frequency and intensity in Western and Central Europe, and decreasing storminess over the North Atlantic north of 60° and in Southern Europe<sup>8</sup>. Evidence of changing storminess from a growing number of studies outside the North Atlantic includes a northward shift in Western North Pacific tropical cyclone exposure towards the East China Sea<sup>9</sup> and increased post-Monsoon storminess in the Arabian Sea<sup>7</sup>. However, substantial uncertainties in storminess projections remain, and represent a real barrier to effective assessment of global fishery vulnerability.

The uncertainty surrounding the changing nature of storm hazards is paralleled by a lack of knowledge about how storm events directly interact with social and economic variables to influence the behaviour of fishers. In addition, the impacts of storms on marine ecosystems and the linkages by which these cause indirect social and economic perturbations to fisheries are little understood. An interdisciplinary research effort is now required to clarify the climatic, social and ecological dimensions of changing storminess to support the assessment of fishery vulnerability and inform adaptive action.

## **Plotting the course ahead**

We advocate a roadmap drawing on climate science, environmental social science, psychology, economics, and ecology, and based on four interlinked research areas (Fig. 3):

1) developing climate modelling to better understand changing storm hazards; 2) understanding fishers' behavioural response to storms; 3) examining the effects of storms on coastal marine ecosystems and socio-economic linkages; and, 4) assessing fisheries vulnerability and adaptation strategies for changing storminess.

### **Modelling changing storm frequency and severity**

Identifying the risk to fisheries of changes in storminess requires climate models that provide a reliable spatial and temporal view of past and future tropical, extra-tropical and thunder storm frequency and intensity. To achieve this, improvements are required in the explicit representation of the sub-grid scale physical processes by which the most intense storms form and develop, such as convection. Advances in ocean-atmosphere coupled models are also necessary to capture the boundary layer processes that drive storms. Progress is being made in these areas, for instance in developing climate models that better represent the coupled ocean-atmosphere processes in tropical cyclones<sup>10</sup>.

Improving the characterisation of storms in climate models demands finer spatial resolutions and a shortening of time steps, which will intensify the trade-off between resolution and simulation timescale resulting from limited computing resources. Supported by greater computing power, enhanced representation of storms in climate models will improve both reanalysis and predictions of storminess and strengthen our understanding of the influence of climate variability at seasonal to decadal timeframes on storm events.

### **Fishers' behavioural response to storms**

The effect of storms on fisheries is in part a function of fishers' behavioural response to meteorological conditions. The heterogeneity of fisher daily participation and spatial effort decisions in adverse weather conditions for different fishery types, vessel characteristics and social and cultural contexts around the world should be explored. Fishers' decisions on where and when to fish are known to be affected by a complex array of socio-economic factors<sup>11</sup>. However, the way in which fishers make weather-related decisions is poorly

understood. We do not know how projected weather information is used or if it accessible to fishers. It will be important to understand fisher decisions to go to sea, or stay at sea, during storms, how weather conditions affect the distribution of fishing activity, the performance of different gears in adverse weather, and the interaction of physical and economic risk perceptions in decision making.

Explaining the behavioural response of fishers to storms will require the involvement of psychologists, sociologists, anthropologists and economists employing research methods across the epistemological spectrum. Qualitative approaches can unravel the complexity of factors, motivations and processes underpinning decision making. Experimental methods, such as economic choice experiments, offer the potential to reveal how decisions are made where observational data are not readily available, as is the case in many tropical fisheries. The increasing availability of on-board satellite vessel tracking technology and wind and wave hindcast modelled data is creating the potential to model fisher behavioural response to weather conditions at unprecedented fine temporal and spatial resolutions. In addition, the emerging application of agent-based modelling approaches to fisheries could reveal the weather-related behaviour of fleets based on the decisions and interactions of individual fishers.

## **Coastal marine ecosystems and socio-economic linkages**

Storms have the capacity to cause extensive disturbance to marine ecosystems and habitats that support productive fisheries. Several areas require investigation to improve our knowledge in this area. Little is known about the manner in which fish lifecycle events, including spawning migrations, larval growth and dispersal during the planktonic larval phase, and the use of shallow nursery ground habitats, are influenced by storm disturbance. There is some evidence that fish may evacuate storm areas or be redistributed by storm waves and currents (Fig. 1a), but this requires further exploration. Storm-induced fish mortality events, such as the death of 400,000 fish in the Nyanza Gulf of Lake Victoria following post-storm deoxygenation and turbidity in 1984<sup>12</sup>, are poorly understood. Finally,

the way that changing storminess interacts with other marine climate change impacts, including ocean warming, acidification and deoxygenation, to affect marine ecosystems remains unexplored.

Interdisciplinary efforts are required to uncover how direct marine ecosystem impacts link to indirect social and economic impacts on fisheries. Whilst there are examples of storm damage to key habitats, we know little of how this flows through to abundance or catchability of targeted fish species. We lack knowledge of how storm-induced fish distribution changes affect fishery catches, but fishers' logbooks may offer a rich source of data to address this gap.

### **Vulnerability and adaptation strategies**

Assessing the vulnerability of fisheries to changing storminess is essential for prioritising limited adaptation resources and informing adaptation strategies. The exposure of fisheries will vary spatially with projected changes in storm risk, target fish species, the resilience of infrastructure, and the extent of natural and man-made storm defences. It is probable that the impact of changing storminess on fisheries will be socially differentiated, with severe impacts more likely to affect small-scale fisheries. The vulnerability of fisheries to changes in storminess is currently unclear. Fishery vulnerability assessments developed over the last decade have acknowledged, but not reflected, changing storminess<sup>13</sup>, largely because of the gaps in knowledge outlined here. These assessments can be enhanced by incorporating appropriate measures of exposure, sensitivity and adaptive capacity to storms.

Fishery adaptation measures will require evaluation in local contexts. Possibilities include technological advances, improvements in the accuracy and communication of weather forecasts, and innovative financial solutions. In Kerala, India, a weather forecast service called 'Radio Monsoon'<sup>14</sup> provides daily information over loudspeaker in harbours and through social media. Insurance schemes triggered by environmental indexes are growing in popularity in terrestrial agriculture<sup>15</sup> and could increase fishery resilience to increased

storminess. Modifications of this concept would have to reflect the nature of daily harvesting activity and the dynamic nature of marine resources. Some fishers may also have opportunities to adapt to take advantage of reduced storminess, which may exacerbate existing challenges to sustainable natural resource use.

## **Conclusion**

Greater attention to the research priorities outlined here could help inform adaptation and protect the well-being of billions of people worldwide. Although scientists are actively working in some of these areas, research gaps remain, and existing knowledge is yet to be applied to this social-ecological climate issue. The potentially catastrophic impacts of changing storminess for global fisheries across relatively short timescales mean that enhanced integration across disciplines is urgently needed to address this challenge.

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## **Author Contributions**

N.C.S. researched and wrote the paper. All authors contributed to the concept, the drafting and approved the final draft for submission.

## **Competing Interests statement**

J.K.P. is a co-chair of the “ICES-PICES Strategic Initiative on Climate Change Impacts on Marine Ecosystems” and will be a Lead Author for the “Small Islands” chapter within the IPCC 6th Assessment Report (AR6 – WGII).



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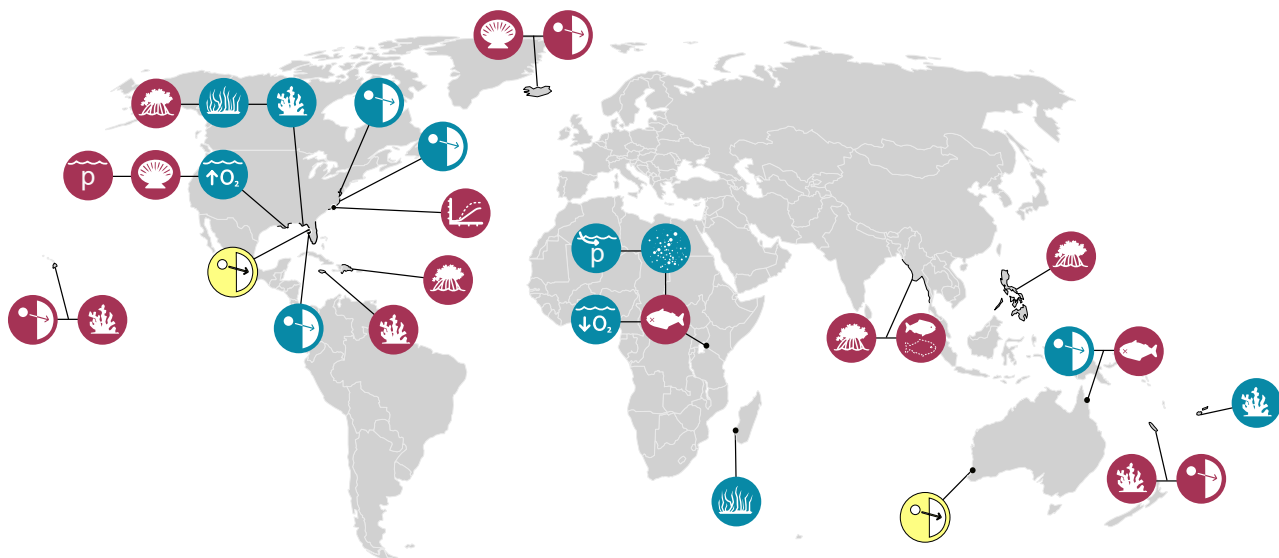
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**Figure 1. Ecological, social and economic impacts of storms on fisheries. (a) Examples of storm-induced marine ecosystem disturbances. For further detail see Supplementary Information Section 1a. (b) Examples of social and economic impact case studies from the 21<sup>st</sup> century. Case studies were selected based on scale of impact, global geographic spread and availability of data. For further detail see Supplementary Information Section 1b.**

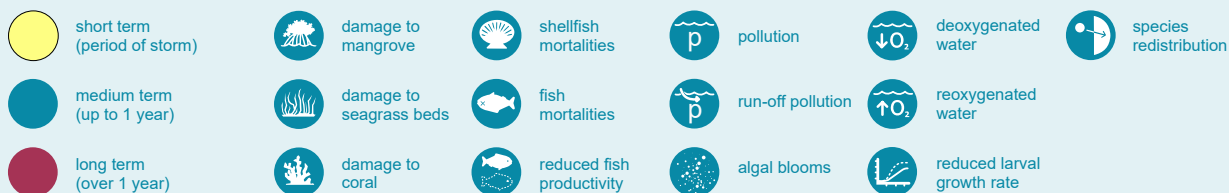
**Figure 2. A selection of reanalysis and projection studies of storminess from across the world demonstrating the spatially heterogeneous nature of changing global storminess. The selection of studies is not systematic but is designed to reflect a range of studies carried out for the Atlantic, Pacific and Indian Oceans, which account for the majority of global fish catch. Darker colours represent changes in the most intense storms. Letters next to symbols indicate changes in frequency (F) or Intensity (I). For further detail see Supplementary Information Section 2.**

**Figure 3. Schematic of a research roadmap to understand the impact of changing storminess on fisheries. Straight arrows between boxes demonstrate the dependencies within and between research streams. Curved arrows represent the feedback loop in which changes in fisher behaviour affect the ecosystem and changes to the ecosystem affect fisher behaviour. Collaboration will be required between research streams. The order of research streams does not represent importance or priority.**

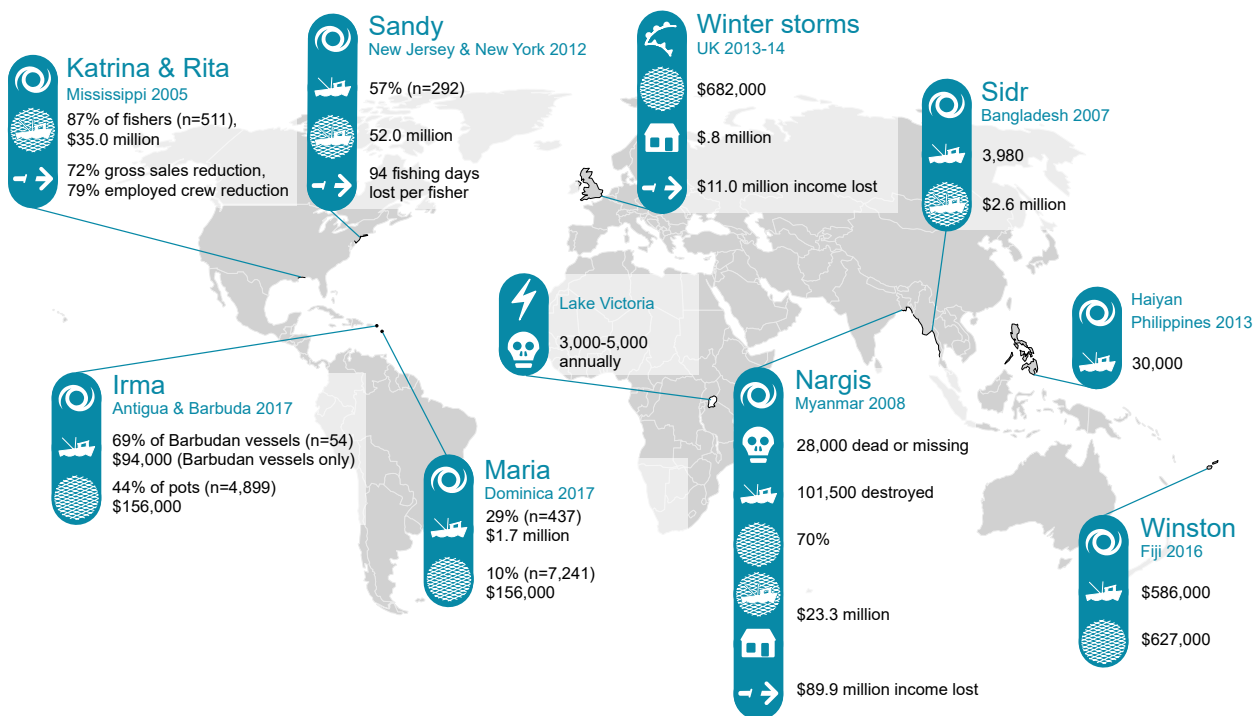
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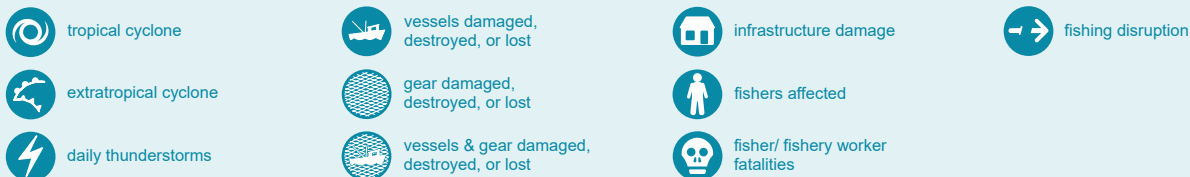
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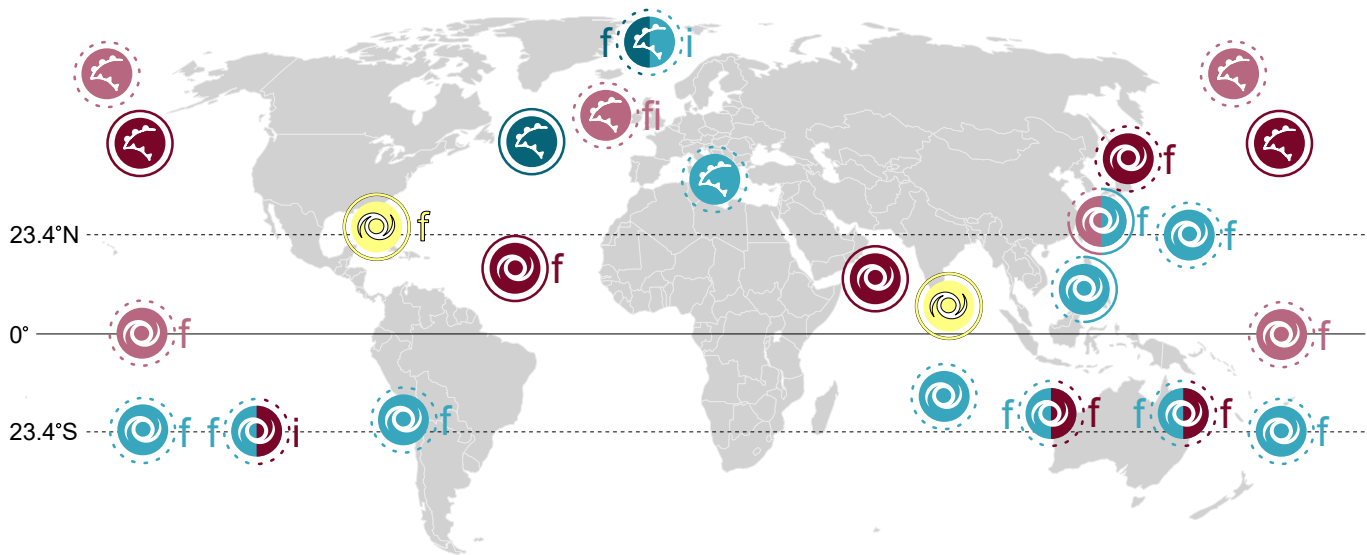


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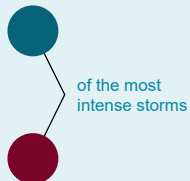
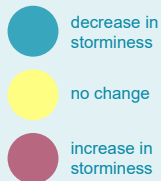


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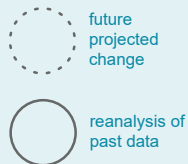




## KEY



i change in intensity  
f change in frequency



## Current storminess

## Future projections

## Achievements

### Storm climate modelling

Representation of physical storm processes, underpinned by finer spatial and temporal scale climate models

Advances in ocean-atmosphere coupled climate models

Fine spatial and temporal scale projections of future storm exposure

### Fisher's behavioural response to storms

Baseline observational studies of current responses to storms across fishery types and social and cultural contexts

Interaction of weather with social, economic, ecological and technological factors to influence fisher participation and spatial-temporal effort

Projections of changes in fisher behaviour, marine ecology and social and economic impacts on fisheries in potential future storm climates

### Ecosystem impacts & socio-economic linkages

Baseline studies of direct storm impacts on fish ecology and marine habitats

Effects of interaction between changing storminess and other climate stressors on marine ecosystems

Indirect social and economic impacts of storm-related marine ecosystem changes

Vulnerability assessments reflecting risks and opportunities of a changing future storm climate

### Vulnerability & adaptation

Indicators of storm risk exposure, sensitivity and adaptive capacity

Vulnerability assessments based on current storm exposure, sensitivity and adaptive capacity

Evaluation of storm adaptation measures in local contexts

For global fisheries:

- Reduced uncertainty in future projections of storm climates at fine spatial scales over decadal to centennial timeframes
- New insight into storm climate variability over seasonal to decadal timeframes
- Established understanding of how storms affect marine ecosystems and the linkages by which these impact fisheries
- Policy-relevant adaptation strategies identified and evaluated

*Increasing confidence in the impact of storms on fishery socio-ecological systems*